Did Cosmic Rays Reionize the Intergalactic Medium?

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Abstract

We investigate the role of cosmic rays from young galaxies in heating and ionizing the intergalactic medium (IGM) at high redshift. Using the IRAS observations at $60\mu m$, we estimate the cosmic ray luminosity density at the present epoch. We consider various forms of luminosity evolution in redshift and calculate (a) the thresholds corresponding to the upper limits of Gunn-Peterson optical depth, (b) the Compton y parameter for an IGM heated by cosmic rays and compare with the upper limits from COBE measurements and (c) an estimated limit from the integral of metal enrichment. We show that certain models, with rather strong evolution and early formation of galaxies, allow reionization of the IGM, consistent with all known constraints.

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1. Introduction

The spectra of quasars provide us with fascinating clues about the intergalactic medium (IGM) at high redshift. The well-known absence of Gunn-Peterson H Lyα absorption troughs in such spectra is the evidence that the IGM has been highly ionized since, at least, the epoch of the highest redshift quasars ($z \sim 5$) (Gunn & Peterson 1965; Steidel & Sargent 1987; Jenkins & Ostriker 1991). On the other hand, in the standard model of big bang cosmology, the universe recombined at a redshift of ~ 1100, leaving only a residual fractional ionization $\sim 10^{-4}$ (Peebles 1968). To reconcile the theory and the observations, astrophysicists over the years have suggested various models of reionization of the IGM.

Quasars and young galaxies have been considered as candidate sources for producing ionizing radiation needed to photoionize the IGM. A metagalactic UV radiation has also been inferred from the "proximity effect", the measured decrease in the number of Lyα clouds in the neighbourhood of a quasar due to its ionizing radiation. It seems that the uncertainties in our knowledge of quasars, galaxies at high redshift and the Lyα clouds are too large to either confirm or rule out the scenario (Miralda-Escudè & Ostriker 1990; Madau 1992; but also see Shapiro & Giroux 1987). Apart from galactic radiation, heating of the IGM by cosmological blastwaves (Ostriker & Ikeuchi 1983) and decaying massive neutrinos (Sciama 1990) have also been suggested as the possible causes of ionization.

In this paper, we ask the question whether cosmic radiation from young galaxies at high redshift played any role in reionizing the IGM. Star formation in the early universe almost certainly produced cosmic ray particles through various acceleration mechanisms. Unlike photons the cosmic ray particles can ionize neutral atoms many times as they move in the IGM. Besides, the gas can be collisionally ionized after being initially heated by cosmic rays. The question is also motivated from the point of view of energetics. Miralda-Escudè & Ostriker (1990), in their study of ionizing radiation from young galaxies, estimated that $\sim 10^{-3}\, M_\odot c^2$ of energy in ionizing photons is emitted for each $1 M_\odot$ of metals produced. Absorptions inside and outside the galaxy, and other losses, though, tend to attenuate the radiation intensity to some extent. If we note that $0.1 M_\odot$ of metals is produced per 10^{51} ergs in supernovae shockwaves and assume that ~ 0.1 of the total shockwave energy is in the form of cosmic rays, we get $\sim 6 \times 10^{-4}\, M_\odot c^2$ per $1 M_\odot$ of metals produced. Naturally,only a fraction of this energy is finally available for heating the IGM, as in the case of photons, but the estimate indicates that cosmic rays could be important as well.

It is interesting to note that Ginzburg & Ozernoy (1965) had already considered an IGM heated by cosmic rays from young galaxies, before the Gunn-Peterson test was applied to the quasar spectra. They used cosmic ray energy densities of $10^{-15\pm1}$ erg cm^{-3} and speculated upon a highly ionized universe. In the three decades since their work, our knowledge of the universe at redshifts $z5$ has increased dramatically and better observational constraints on the physical state of the IGM at these redshifts have been obtained. In this paper, we consider the problem of the cosmic ray heated IGM in the light of the new data. We estimate the cosmic ray energy density from the IRAS observations of the $60\mu m$ luminosity function of galaxies, include heating and cooling processes previously neglected. We present the results in the form of threshold contours for various observational limits in the plane of the IGM density and evolution parameters.

The organization of the paper is as follows. In section 2. we set up the necessary equations, discuss the spectrum and the energy density of cosmic rays. In section 3, we calculate the heating and ionization and then discuss various implications of an IGM heated by cosmic rays in section 4.

2. Preliminaries

2.1 Equations for ionization by cosmic rays

It is almost certain that young galaxies at high redshift produced cosmic rays as the Milky Way does now. It is, however, an important point as to how much of the energy in the form of cosmic rays leaked out of the galaxies to the intergalactic medium, and how. The effect of cosmic rays on the IGM depends crucially on the spectrum, the lower energy cutoff and the total cosmic ray luminosity that finally emerges from the galaxies.

The fraction of the total brightness in cosmic rays that is put into the IGM and the lower cutoff of energy, depends on the mode of leakage from the galaxies. One possibility is that of their being carried by galactic winds, in which case the particles will lose energy due to adiabatic expansion ($p \sim r^{-1}$). This mode of transportation lowers the cutoff energy as well as the total energy. We define β_l as the lower cutoff in β ($= v/c$) of the particles after emerging from the galaxies.

Other important variables in the process of IGM heating by cosmic rays are (a) h (Hubble constantat the present era is defined as $H_o = 100h$ km s^{-1} Mpc^{-1}), (b) the global Ω of the universe, (c) Ω_{IGM}, the density of the IGM in the units of critical density ($\rho_c = 3H^2/8\pi G$), (d) z_s, the epoch of galaxy formation, and (e) the evolution of cosmic ray luminosity of galaxies. Ω_{IGM} is certainly less than Ω_b, the density in baryons, which, according to current estimates based on primordial nucleosynthesis (Kolb & Turner 1990), is equal to $(0.06 \pm 0.02)(h/0.5)^{-2}$. For simplicity, we consider an Ω_{IGM} which is constant in time.

Consider the IGM in which cosmic rays with luminosity $f_{cr}\ L_{cr}(z)$ (erg cm^{-3} s^{-1}) is deposited by the galaxies beginning at z_s. Here f_{cr} is the dilution factor due to the adiabatic energy loss of cosmic rays in the wind. The particles have a $p^{-\alpha}$ spectrum and we express their differential number density by $\frac{n_{cr}(\beta_i)}{E(\beta_l)}\, d\beta_i$, where β_i is the initial β of a particle (i.e. before it interacts with the IGM) and $E(\beta_l) = \int_{\beta_l}^{1} E(\beta_i) n_{cr}(\beta_i) d\beta_i$ in the denominator normalizes the spectrum.

The particles lose energy as they move in the IGM due to various processes as we will soon explain in detail. The energy of a particle, at any instant z, therefore depends on (a) z_e ($z < z_e < z_s$), the redshift at which it was emitted, (b) its original energy, or, rather, in terms of velocity, β_i and (c) z, the current redshift. In the following sections, we will inject cosmic rays with certain initial energy density, follow their evolution in time and at each time step, integrate the effect of all the cosmic rays injected prior to that instant. The particles ionize the medium with rate, $n_{HI}(z)\sigma[\beta(z)]\beta(z)c$. Here $n_{HI}(z)$ is the density of neutral atoms, σ is the ionization cross-section and β ($= v/c$) denotes the velocity of the particles.

The evolution of the energy density of IGM, $\epsilon(z)$ (erg/cm^3), is governed by heating due to ionization (Γ_{ion}), heating from the direct collision of cosmic ray particles with the free electrons (Γ_{cr}) and cooling due to recombination, adiabatic expansion of the universe and line emission of hydrogen atoms ($L(HI)$). The ion-electron relaxation timescale is $\sim 10\, T^{3/2} n^{-1}$ sec, which is smaller than all other relevant timescales. We therefore use $\epsilon = \frac{3nkT}{2}$ as the definition of temperature of the IGM.

The evolution of f, the ionization fraction of the IGM is succinctly expressed by the following set of equations, viz.,

$$n_{tot}(z)\frac{df}{dt} = \int_{z}^{z_s} f_{cr} L_{cr}(z_e)\Big(\int_{\beta_l}^{1} d\beta_i\, \frac{n_{cr}(\beta_i)}{E(\beta_l)}\{n_{HI}(z)\sigma[\beta(z,z_e,\beta_i)]\beta(z,z_e,\beta_i)c\}\Big) dz_e$$
$$+ 7.8\times 10^{-11} n_e n_{HI} T^{1/2} \exp(\frac{-13.6\text{eV}}{kT}) - \alpha_{rec} n_e n_{HI}, \quad (1)$$

$$-\frac{d\beta}{dt} = 1.94\times 10^{-16} n_{HI}(z)\, \frac{(1-\beta^2)^{3/2}}{\beta} \frac{2\beta^2}{((0.01)^3 + 2\beta^3)}(1 + 0.0185 ln\beta H[\beta - 0.01])$$
$$+ 3.27\times 10^{-16} n_e(z)\, \frac{(1-\beta^2)^{3/2}}{\beta} \frac{\beta^2}{x_m^3 + \beta^3} + \frac{\beta}{(1+z)}\frac{dz}{dt};$$
$$x_m = 0.0286(T/2\times 10^6 K)^{1/2}, \quad (2)$$

$$\frac{d\epsilon}{dt} = -\Big(\frac{\epsilon}{t_{rec}}\Big) - \Big(\frac{5\epsilon}{(1+z)}\frac{dz}{dt}\Big) - L(HI) + \Gamma_{cr} + \Gamma_{ion} \quad (3)$$

$$\frac{dz}{dt} = \frac{1}{H_o}\frac{1}{(1+z)^2(1+\Omega z)^{1/2}} \quad (4)$$

The ionization cross-section for protons in equation (1) is given by (in the units of πa_o^2, where $a_o = 5.3 \times 10^{-9}$ cm, is the Bohr radius and x, the kinetic energy in keV)

$$\begin{aligned}\sigma &= \frac{1.393 \times 10^{-4}}{\beta^2}\Big(6.2 + Log\frac{\beta^2}{(1-\beta^2)} - 0.43\beta^2\Big), \quad \beta \geq 0.026 \\ &= 3.455 - 0.0386x + 0.01347x^2 - 2.463 \times 10^{-3}x^3 + 1.75 \times 10^{-4}x^4, \\ &\quad 0.0115 < \beta < 0.026 \end{aligned} \tag{5}$$

The expression in the first line of equation (5) is given by Spitzer & Tomasko (1968) and that in the second line is an analytical fit for the data given by Fite et. al (1960). Following Spitzer & Tomasko, we multiply the cross-section by $\frac{5}{3}$ to allow for ionizations by the secondary electrons, and by an additional factor of 1.89 for ionizations by heavy ions. The factor of $\frac{5}{3}$, to be precise, is not a constant and varies with the fractional ionization (1.67 for $f \sim 0$ and ~ 1.12 for $f \sim 0.3$ (Spitzer and Scott 1969)), but the discrepancy is expected to be of the order of unity.

The second term on the right hand side of equation (1) is due to collisional ionization in a gas with temperature T. The last term denotes recombination with $\alpha_{rec} = 2{\times}10^{-11}T^{-1/2}$ cm^3 s^{-1}.

The first term in equation (2) represents the loss of energy of cosmic rays due to ionization (H is the Heaviside function) while the second term denotes the loss of energy due to Coulomb interactions with free electrons (Mannheim and Schlickeiser 1993). The last term is due to the expansion of the universe.

The heating due to ionization, Γ_{ion}, depends on the mean energy of the electrons and the probability of energy loss in inelastic collisions. For small values of f, $\Gamma_{ion} = 5{\times}10{-}12I$ erg cm^3 s^{-1}, where I (cm^{-3} s^{-1}) is the rate of ionization, and for $f > 0.1$, Γ_{ion} is an order of magnitude higher. However, Γ_{cr}, the heating due to direct collisions of cosmic rays with free electrons, dominates all heating processes for $f0.1$. We use $\Gamma_{cr} = -\int \frac{dE(\beta)}{dt} n_{cr}(\beta) d\beta$, where $\frac{dE(\beta)}{dt}$ is the Coulomb loss for a cosmic ray particle with velocity $c\beta$ from the second term on the right hand side of the equation (2). $L(HI)$ is the rate of line cooling by hydrogen atoms at $937.8, 949.7, 972.5\mathring{A}$ (Gaetz and Salpeter 1983).

2.2 Cosmic Rays – energy density, spectrum and leakage

The luminosity function of galaxies at $60\mu m$ provides an estimate for $L_{cr}(z = 0)$. The luminosity in far infrared wavelengths can be scaled to that in cosmic rays from the observations of M82. Kronberg et al (1985) estimated a supernova rate of ~ 1 per 3 years in M82 with an uncertainty of a factor of three. Assuming that the efficiency of producing cosmic rays is about 10% and the energy input per supernova is 10^{51} ergs, we obtain the cosmic ray luminosity of 10^{42} ergs s^{-1}. Comparing this with the $60\mu m$ luminosity of M82 of $4 \times 10^{10} L_\odot$ (Rieke et al 1980), we get a ratio of 0.007 between the cosmic ray and far infrared luminosity. We will use a ratio of 0.01 and discuss the effect of the uncertainties in section 3.5.

Lawrence et. al. (1986) fitted their IRAS data with the luminosity function,

$$\phi(L) = CL^{-1}(1 + \frac{L}{L_* b})^{-b}, \tag{6}$$

where $\phi(L)$ is defined such that $\phi(L) dlog_{10} L$ is the number of sources per Mpc^{-3} in the luminosity range $log_{10} L, log_{10} L + dlog10L$. The unit of L is $L_\odot = 3.9 \times 10^{33}$ erg s^{-1}. They obtained their best fit with $b = 2.4$, $logL_* = 11.3$, $logC = 7.12$. Integration with their observed lower cutoff at $log_{10} L \sim 7.5$ yields a luminosity density of $1.6 \times 10^{-32} h$ erg cm^{-3} s^{-1}. The scaling discussed above then gives a cosmic ray luminosity density of $1.6 \times 10^{-34} h$ erg/s/cc at $z = 0$. This is the value we adopt for $L_{cr}(z = 0)$ in equation (1).

The spectrum of cosmic rays outside the galaxy is the same as the source spectrum in the simple leaky box argument. While there are obvious problems with such an argument (see Biermann 1993), there are no better alternatives at present. Biermann (1993) (and other papers in the series) has discussed the acceleration of cosmic rays and the predictions have been verified with airshower data. The basic idea discussed in these papers is that cosmic rays (a) up to about 10 TeV particle energy (for hydrogen) are dominated by normal supernova explosions in the interstellar medium, (b) from 10 TeV to near EeV particle energies are dominated by supernova explosions into stellar winds, and (c) beyond EeV particle energies are dominated by radio galaxies. For the low energy cosmic rays this means that their spectrum is $\sim E^{-2.4}$ at injection, and again outside the galaxy. Note that this injection spectrum is the relativistic approximation. The theory of shock acceleration (e.g., Drury 1983), however, tells us that the injection spectrum is actually a power law in momentum across the transrelativistic region, i.e., $p^{-2.4}$.

For the lower energy cutoff in the spectrum there are two arguments. First, one needs a lower cutoff in the range of $30 - 100$ MeV bundances in intersteller clouds (for example, Black et al 1990) repeating the arguments of Spitzer & Tomasko (1968) (Jokipii & Biermann, in preparation). Second, the production of Be and other elements from spallation by cosmic rays indicates an energy cutoff in the same range (Gilmore et al 1992).

We thus adopt a cosmic ray spectrum of $\sim p^{-2.4}$ and a low kinetic energy cutoff of 30 MeV ($\beta = 10^{-0.6}$). We will discuss the consequences of the uncertainties in these values in section 3.5.

Let us here note that in the case of galactic winds carrying the cosmic ray particles, the fraction f_{cr} of the total energy that is put into the IGM, is a function of the ratio between the lower cutoff in particle momentum inside and outside the galaxy. With $p \sim r^{-1}$ (

where r denotes length scale) the lower cutoff and the flux ($n(p)\beta c dp$) decrease as the particles lose energy adiabatically expanding into the IGM. The fraction f_{cr} is simply the ratio of the energy contents of these two particle spectra, inside and outside the galaxy. After fixing the lower cutoff inside the galaxy, f_{cr} therefore becomes a function of β_l.

In a galactic wind, adiabatic loss of the cosmic rays dominates over their ionization loss. The energy of the non-relativistic particles scale as $E \sim p^2 \sim (r/r_o)^{-2}$, where r_o is some fiducial length scale. The density of particles is given by $n \sim n_o(r/r_o)^{-3}$ (from the conservation of number of particles in a spherically symmetric wind). The number of times a cosmic ray particle has ionizing collisions is $\sim \int_{r_o}^{r_f} n\sigma dr$ which, for a final radius $r_f \gg r_o$, is $\sim 0.5 n_o \sigma r_o$. A value of $\sigma \sim 10^{-18}$ cm^2, $r_o = 1$ kpc and $n_o = 1$ cm^{-3} should give us an upper limit on the ionization loss. With ~ 50 eV lost per ionization, this gives ~ 25 keV, which is negligible for a $\sim$ few MeV particle compared to the adiabatic loss. The low energy cosmic rays therefore are carried by the galactic winds to the IGM with energy lost mainly by the adiabatic expansion and we neglect the ionization loss inside the galaxy and in the wind.

3. Results

3.1 Approximate considerations:

Let us first try to estimate the heating by cosmic rays before solving the equations exactly. Following Ginzburg and Ozernoy (1965), for cosmic ray energy densities of w_{cr} (eV/cm^3) with all the protons having energy E_{cr}, the heating due to cosmic rays can be approximately written as,

$$\Gamma \approx 10^{-11} n w_{cr} \Big(\frac{E_{cr}}{1\mathrm{MeV}}\Big)^{-3/2} \frac{\mathrm{eV}}{\mathrm{cm}^3\ \mathrm{sec}}. \qquad (7)$$

Here n is the particle density. As we have seen in the previous section, the local energy density in cosmic rays is around a hundredth of that in $60\mu m$, i.e., $w_{cr} \sim 10^{-5}$ eV cm^{-3}; The dilution factor $f_{cr} \sim 0.1$ for a decrease in the lower energy cutoff to ~ 1 MeV from an initial cut off of $\sim 30 MeV$ inside the galaxy. With no luminosity evolution, a cosmic ray energy density of 10^{-6} eV cm^{-3} seems reasonable to be used in (7). Therefore, over a Hubble time ($t_H \sim 4 \times 10^{17}$ sec for $h = 0.5, \Omega = 1$), the cosmic rays put ~ 4 eV per particle in the universe. However, the approximation of using all the protons at the lower energy end overestimates Γ by an order of magnitude, as we will show in section 3.2, and the energy per particle in this case is about 0.5 eV.

Without any evolution in luminosities, the cosmic ray energy density thus is not enough to heat up the IGM to high temperatures to ionize collisionally. However, the above estimate shows that if w_{cr} is larger by a factor of ~ 50 due to moderate evolution, the IGM can be heated up to $T10^5$ K. Collisional ionization then will rapidly deplete the neutral atoms of hydrogen.

3.2 Heating and Ionization of the IGM and the Gunn-Peterson Test:

The Gunn-Peterson optical depth due to neutal hydrogen at z can be written as,

$$\tau_{GP} = 4.6 \times 10^5 \Omega_{IGM} h(1-f)(1+z)^2(1+\Omega z)^{1/2}, \tag{8}$$

where $(1-f)$ is the neutral fraction. It is evident that the optical depth rises steeply with z and the test becomes most sensitive at high redshifts. The highest redshift at which τ_{GP} has been measured is at $z = 4.2$ and the upper limit is $\tau_{GP} < 0.14$ (for $h = 0.5$) (Jenkins and Ostriker 1991). Webb et. al's (1992) measurement of $\tau_{GP} = 0.04$ at $z = 4$ is dependent on the assumptions on the spectrum of Lyα clouds which are yet to be confirmed and we use the former upper limit of τ_{GP}.

We consider three forms of evolution and calculate the thresholds for the above limit of τ_{GP} at $z = 4.2$.

Case I: Here, we assume the luminosity function to have a single power law, i.e.,

$$L_{cr}(z) = L_{cr}(z=0)(1+z)^{3+m} \qquad z \leq z_s. \tag{9}$$

The threshold contours in the $(\Omega_{IGM} - m)$ plane are shown in fig. 1(a) for $1 + z_s = 8, 10$ and $\Omega = 0.1, 1.0$.

Case II: In this case we assume the evolution to have a "broken" power law: with an index m till a certain redshift z_c when the evolution is "switched off", and the galaxies simply comove beyond z_c. That is,

$$\begin{aligned} L_{cr}(z) &= L_{cr}(z=0)(1+z)^{3+m} \qquad z \leq z_c \\ &= L_{cr}(z=z_c)(1+z)^3 \qquad z_c < z \leq z_s. \end{aligned} \tag{10}$$

Recent observations of high redshift quasars have indeed found their evolution to have a "broken" power law luminosity evolution, with $z_c \sim 2-3$ and $m \sim 3.5$ (Boyle 1991). Contours are shown in the $(\Omega_{IGM} - z_c)$ plane for $1 + z_s = 10, 8, m = 4$ and $\Omega = 0.1, 1.0$ in fig. 1(b)

Case III: Following Miralda-Escudè and Ostriker (1990), we consider the case where galaxy formation rate per unit redshift is a Gaussian, $\phi(z)dz \propto \exp[-\frac{1}{2}(\frac{z-z_f}{w})^2]dz$. Conceivably, $L_{cr}(z)$ could also be a Gaussian of the above form, i.e.,

$$\begin{aligned} L_{cr}(z) &\propto (\text{Constant}) \exp[-\frac{1}{2}(\frac{z-z_f}{w})^2]\,(1+z)^3 \\ &= L_{cr}(z=0) \exp[-\frac{1}{2w^2}((z-z_f)^2 - z_f^2)]\,(1+z)^3. \end{aligned} \tag{11}$$

Contours in the $(\Omega_{IGM} - w)$ plane are shown in fig. 1(c) for $1 + z_s = 1 + z_f = 10, 8$ and $\Omega = 0.1, 1.0$.

It is evident from fig. 1 (a, b,c) that, in general, a lower value of Ω corresponds to contours with small evolution. This is because in an older universe (i.e., lower Ω) the cosmic rays have more time to ionize and heat the IGM for the same range of redshift. The curves also show that stronger galactic winds can heat and ionize the IGM more easily.

As was pointed out in the last section, most of the heating occurs after the cosmic rays ionize the IGM to $f0.1$. Heating by Γ_{cr} and collisional ionization then both act to raise f. At temperatures $\sim 10^4$ K, line cooling of neutral hydrogen is important but its effect diminishes with increasing f. The recombination timescale ($\sim 5.0 \times 10^{17}(1+z)^{-3}h^{-2}\Omega_{IGM}^{-1}(T/10^4)^{1/2}$ sec) is large compared to other cooling timescales and is therefore less important. Cooling due to the expansion of the universe becomes important only at lower redshifts. To illustrate the effects of various heating and cooling mechanisms, we plot in fig. 2., the temperature of the IGM, various cooling and heating terms as functions of redshift, for the case of $L_{cr} \propto (1+z)^{m+3}, m = 3, 1+z_s = 10, \Omega = 0.1, \Omega_{IGM} = 0.01, h = 0.5$.

It is useful to calculate the the fraction of the total energy in cosmic rays that is lost to the IGM. For evolutions of the type Case I above, we find that the fraction depends on the lower cutoff β_l and Ω, Ω_{IGM} and it is fairly insensitive to the initial redshift z_s, the evolution index m, the cosmic ray spectrum index α. From equation (3.1), it is easy to see that the fraction $\frac{\Gamma_{cr}}{w_{cr}} t_H \propto \Omega_{IGM}$ and is bigger for an older universe (i.e., smaller Ω). The exact dependence on β_l and Ω_{IGM} is plotted in fig. 3. Equation (7) predicts, for example, for $\Omega_{IGM} = 0.01, \Omega = 1., h = 0.5, \beta_l = 10^{-1.3}$, that a fraction ~ 0.1 of the cosmic ray energy density to be lost in moving through the IGM. Considering the fact that for $\beta_l = 10^{-1.3}$, $f_{cr} \sim 0.1$, the plot shows that the approximate expression in equation (7) overestimates the energy loss by an order of magnitude.

Theories of galaxy formation have not yet acquired the finesse to be able to predict the form of evolution of the luminosity function. Recent IRAS observations have shown evidences (for example, Lonsdale, C. et.al 1990) for the evolution index being $m = 3 - 4$ with a cutoff at $z_s \sim 3$. The fit to the data is fairly insensitive to the cutoff z_s since mostly galaxies at $z < 1$ contribute to the data. As the curves of fig. 1 show, the reionization of the IGM by cosmic rays needs the evolution index m to be as large as this but with an epoch of galaxy formation much earlier. However, due to the uncertainty in interpreting these data, we will not use them as observational constraints. We will calculate the effects of luminosity evolution on the IGM and compare with the constraints from COBE and abundances heavy elements in the universe in the next sections.

3.3 COBE limit

Recent measurement of the Compton y parameter of the microwave background radiation with COBE has put severe constraints on the history of a hot IGM. An upper limit of

$$y = \int \frac{n_e kT}{m_e c^2} \sigma_{Th} c\, dt \; < 2.5 \times 10^{-5} \tag{12}$$

has been reported (Mather et al 1993). A high cosmic ray energy density could heat up the IGM to temperatures which are ruled out by such a limit. We show in fig. 1 (a,b,c). the curves corresponding to the above limit on y. The regions bounded by these curves and the threshold curves for the upper limit of τ_{GP} are the allowable regions for an IGM heated by cosmic rays.

The curves show that, for Case I, with the single power law evolution, the Gunn-Peterson and the COBE limit exclude an hot and collisionally ionized IGM with Ω0.1. For the "broken" power law case, however, the limits are not stringent for $m = 4$, the case we have considered. For higher values of m, both Gunn-Peterson and COBE limit lines will shift towards lower values of $1 + z_c$. With a Gaussian form of evolution, COBE limit curves, again, approach the τ_{GP} curves at high Ω_{IGM}.

We found that for the points on the τ_{GP} threshold contours for Ω_{IGM}0.05, the values of the Compton y parameter are about a hundredth of the current upper limits.

3.4 He II Gunn-Peterson test:

The optical depth due to singly ionized helium atoms in the IGM, if observed in the near future, can put interesting constraints on the physical state of the IGM and its history. The optical depth for the Lyα line of HeII (304$\AA$) is given by

$$\tau_{HeII} = 7.7 \times 10^2 \frac{n_{HeII}}{n_{He}} \Big(\frac{\Omega_{IGM}}{0.01}\Big)(\frac{h}{0.5})(1+z)^2(1+\Omega z)^{-1/2}, \tag{13}$$

assuming a 25% helium abundance. In ionization equilibrium at $T \sim 10^{5.5}$ K, the fractional abundance of HeII is $\sim 10^{-3.3}$. Therefore, for an IGM at such a temperature at z, the optical depth will be

$$\tau_{HeII} \sim 3.9 \times 10^{-2} \Big(\frac{\Omega_{IGM}}{0.01}\Big)(\frac{h}{0.5})(1+z)^2(1+\Omega z)^{-1/2}. \tag{14}$$

It is much smaller than that in most of the models considered by Miralda- Escudè and Ostriker (1990) for a photoionized IGM. The He II Gunn-Peterson test, however, is feasible only for redshifts more than two for the wavelength of the photons need to be long enough to avoid absorption in our Galaxy.

3.5 Uncertainties

It is easy to see the effects of using different values of the parameters that we have used. The Gunn-Peterson limit curves in fig. 1 show the balance between the effect of collisional ionization ($\propto n^2 \sim \Omega_{IGM}^2 h^4$) and the optical depth ($\propto \Omega_{IGM} h$). The curves, therefore, scale as $\Omega_{IGM} h^3$. In other words, for a change in h by a factor a, points in the curves at a certain Ω_{IGM} would shift to $a^3 \Omega_{IGM}$. The COBE limit curves scale as $\Omega_{IGM} h$ since $y \propto n t_H$. The allowable regions between the curve, thus, become narrower with increasing h and make IGMs with higher Ω_{IGM} more difficult to reconcile with both τ_{GP} and y limits.

The calibration of cosmic ray luminosity from the observations of M82 has an uncertainty of about a factor of three. As the effect of collisional ionization is proportional to $n^2 w_{cr}$ the curves corresponding to τ_{GP} and y scale as $a^{1/2} \Omega_{IGM}$ where a is the factor of uncertainty in the luminosity. We have checked that numerical calculations validate these qualitative arguments. The effect of changes in the spectral index α for the cosmic rays by an amount ± 0.1 is small enough to be neglected. Also, a change by a factor of ~ 3 in the lower energy cutoff corresponds to a change by $\sim 10^{0.23}$ in β_l and the change is expected to be of the same the order as between the curves of different β_l.

4. Discussions

As we noted in section 1, the amount of heavy element enrichment in the universe can be associated with the cosmic ray energy density. We have already seen that $1 M_\odot c^2$ ergs of energy corresponds to the production of $1 M_\odot$ of metals produced in supernova explosions. If we take a mean metal density of 2×10^{-32} g cm^{-3} (corresponding to $\Omega_b = 0.1$ and mean metallicity equal to 0.02) we get an upper limit on the cosmic ray energy density of 10^{-14} ergs cm^{-3}. To show how this limit constrains the scenario of cosmic ray heating of the IGM, we have drawn corresponding vertical lines in the plots of fig. 1 (allowable regions are to the left of the plotted lines). One must bear in mind that this constraint is at best a crude one, depending on the assumptions of the mean metallicity, Ω_b and the fraction of supernova explosion energy going into cosmic rays. If the estimates are not very far from reality, then they give stronger limits than the COBE measurements. Note that, since in this model one needs strong galactic winds to carry the cosmic rays out to the IGM, one expects a nontrivial enrichment of the IGM as well.

Another possible constraint is that the high energy tail of the intergalactic cosmic rays originating in galaxies should not dominate over the galactic cosmic rays since heavy elements have been found to be abundant in that regime (Stanev et. al 1993).

In the above calculation, we have considered an isotropic distribution of cosmic rays and a homogeneous IGM. It is interesting to speculate upon the effects of clumpiness in the cosmic rays as well as in the IGM. The galactic winds carrying the cosmic rays will have to emerge out of the clumps, which have higher densities, to produce any noticeable heating and ionization. Cosmic rays could achieve this more easily than the photons in a photoionized IGM.

Inhomogeneities in the IGM may lead to formations of pockets of gas with high neutral fraction (at high density pockets the gas would cool faster) and may show local Gunn-Peterson absorption troughs. The inhomogeneities would also impart anisotropies ($\frac{\Delta T}{T}$) in the microwave background radiation of the order $\sim 2y$ (i.e., $\sim 5 \times 10^{-7}$ for points on the threshold curves for τ_{GP}) in the angular scale that is appropriate for the clumps.

We have also treated the IGM density as a constant in time. The result that ionization of the IGM is easier for very low IGM density also features in the photoionization models. However, whether such a low IGM density at high redshifts can be reconciled with galaxy formation is an important question (Shapiro et al 1991). Our results pertain only to the IGM density at redshifts $z4$, before the era now accessible through the Gunn-Peterson test. Future works on structure formation and evolution of galaxies should shed more light on the problem and constrain the models better.

Conclusion

We have considered the heating and ionization of IGM by cosmic rays from young galaxies. Using the IRAS luminosity function of galaxies at $60 \mu m$ we estimated the local cosmic ray energy density to be $\sim f_{cr} 10^{-5}$ eV cm^{-3}, where f_{cr} is the dilution factor depending on the energy loss in escaping the galaxies into the IGM. We have calculated the effect of low energy cosmic rays, carried outside the galaxy by winds, for different models of galactic evolution. We found that if the energy density were larger (for example, by a factor of ~ 50, for $\Omega_{IGM} = 0.01, \Omega = 0.1, h = 0.5$) at high redshifts due to galactic evolution, heating and ionization of the IGM by cosmic rays would be important.

The observations that constrain such a scenario are Gunn-Peterson tests (for neutral hydrogen, and HeII, in the near future), Compton y parameter from COBE measurements and heavy element enrichment in the universe. We found that COBE and Gunn-Peterson limits provide the strongest constraints and we have shown that there are various models of luminosity evolution of galaxies for which both these limits can be satisfied. In such cases, the IGM is partially ionized and heated to temperatures in excess of 10^5 K which then collisionally ionizes to the Gunn-Peterson limit.

We have calculated the Gunn-Peterson optical depth for HeII in a hot IGM, which may provide, in the future, a test to distinguish between a photoionized and a collisionally ionized IGM.

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Figure Captions

Figure 1 (a): Thresholds contours for $\tau_{GP} < 0.15$ at $z = 4.2$ and those corresponding to $y(z = 0) < 2.5 \times 10^{-5}$ are plotted for the Case I evolution. The solid, dotted and dashed curves are for $\beta_l = 10^{-2}, 10^{-1.5}, 10^{-1.3}$ respectively. (With an initial lower cutoff of 30 MeV, these curves correspond to adiabatic loss of energy in winds by factors of $25, 7.7, 5.0$ respectively.) The set of curves on the left and right correspond to the τ_{GP} and y limits respectively and allowable regions are below the curves. Case I, with a single power law evolution is considered here for $\Omega = 1, 0.1$ and $1 + z_s = 10, 8$.
The vertical dot and dashed lines correspond to the constraints from metal enrichment. Allowable regions are to the left of these lines. The horizontal long dashed lines are the limits on Ω_b (0.006 ± 0.02) from primordial nucleosynthesis $(\Omega_b > \Omega_{IGM})$.

Figure 1(b): Contours for Case II, with a broken power are shown for $\Omega = 1, 0.1$ and $1 + z_s = 10, 8$ and $m = 4$. The curves are in the parameter space of $\Omega_{IGM} - -1 + z_c$.

Figure 1(c): Case III, with a gaussian form of evolution is considered here for $\Omega = 1, 0.1$ and $1 + z_f = 1 + z_s = 10, 8$. The contours here are drawn in $\Omega_{IGM} - -w$ space

Figure 2: Temperature and $\mathrm{Log}_{10}\,(\frac{dT}{dz})$ for various heating and cooling processes are plotted as functions of the redshift z for the Case I, a single power law luminosity evolution with $m = 3., \Omega = 0.1, \Omega_{IGM} = 0.1, h = 0.5, \beta_l = 10^{-1.3}$. The solid curve is $\mathrm{Log}_{10}\, T$; the dash and dot curve is due to cosmic ray heating; the dotted, short dashed, long dashed curves denote cooling due to recombination, expansion of the universe and line cooling respectively.

Figure 3: Fraction of the cosmic ray energy density that is lost in moving through the IGM is plotted against the IGM density. The dotted and dashed curves are for $\beta_l = 10^{-1.5}, 10^{-1.3}$ respectively for the case of a single power law evolution with $m = 3, \Omega = 0.1, h = 0.5$. With an intial lower cutoff of 30 MeV ($\beta = 10^{-0.6}$), these curves then represent adiabatic loss of energy in galactic winds by factors of $7.7, 5.0$ respectively.